

SPACE POLICY ISSUES OF SPACE SOLAR POWER WIRELESS POWER TRANSMISSION

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Abstract

The use of wireless power transmission in Space Solar Power activities creates significant policy issues regarding the beam right-of-way. There will not be a single beam, there may well be hundreds of beams for economical systems. Are some or all of these power beams to be afforded priorities of space for unobstructed power delivery, or must the beaming systems be designed to be capable of detecting any and all potential beam interceptions and appropriately responding? The repeated interruptions for guaranteed safety of transit for freely moving air and space traffic are of great consequence. The safety issues are critical, but also the implications for equipment transient protection, energy storage system costs and the quality of power delivery service are significant for wireless power transmission economics.

A scenario of precursor wireless power transmission developments leading up to and including SSP applications will be used to frame and to discuss the beamed power technology implications and policy issues.

INTRODUCTION

We teach children at an early age the dangers of crossing roads and how and under what circumstances to cross a roadway safely at an intersection, crosswalk, flyover, pedestrian tunnel, etc. Crossing a beam of electromagnetic energy has also been experienced from youth. Visible power beams have been intruding on the populace, in the form of flashlight beams, mirror reflections of sunlight or glints, automotive headlight beams, searchlight beams, visible laser pointers and laser light shows.

Generally, the power flux densities are low and we have learned to blink or look away to avoid damage. However, if Space Solar Power Satellites (SPS) begin importing power to Earth with microwave beams there will be chances for more frequent interception of power beams by aircraft and spacecraft flying through the beams. As space tourism and private exploration grows, there will be more frequent power beam-person encounters, thus space policy must grow to assure safety and to allow for economical industries in such events.

The good news is that you can transfer energy without wires. The sun does it every day. The bad news is that to commercially transport energy without wires in an economic fashion, requires high power flux densities. High power flux densities can be hazardous to persons and equipment.

Freedom of movement has been a hallmark of civilization. Although physical and environmental barriers and governmental impediments or restrictions do exist, it is nice to be able to "move about the country" or to take free flight paths except for restricted air

space for example. However, the public necessity and convenience of restricted right-of-way for methods of power transmission do constrain free movement.

Coal trains, natural gas pipelines, electric utility transmission lines, and hydroelectric streamflow channels all involve significant hazards to unrestricted transit of personnel and equipment. Easements, barriers, posted limits or other constructs are necessary to minimize loss of life or property while permitting commercial power delivery for benefit of the public. Alternate routes around, over or under such power transmission routes are generally provided.

Nevertheless, there is a major distinction of WPT from the above means of power transmission. In particular, for microwave and some laser beams, the wavelength is long enough that the human eye cannot see the beam. One cannot see the electric or magnetic fields around high voltage transmission lines either, but the open wire line conductors provide a visualization of the potentially dangerous region and utility education activities provide knowledge of the potential hazard. (viz. no kite flying with copper wires)

Thus, WPT beams create an insidious hazard. What you can't see may hurt you! Therefore, special efforts must be made to keep personnel and property out of the beam, or provide exclusion barriers or the means to perceive the beam from a distance and knowledge of the dangers.

How shall new concepts be developed or existing ones modified to safely and economically handle wireless power transmission (WPT) beams? What policies are applicable and what new policies should be formulated? What organizations and venues should be used to inform and educate the populace, to debate and develop the necessary balance between unrestricted movement of aircraft and spacecraft and power beams for commercial applications?

This paper will examine these questions by discussing various scenarios for use of WPT beams along a Roadmap leading to and including SPS [1]. Space policy related questions will be addressed at each milestone of the Roadmap of which ground-to-ground power beaming is first.

GROUND TO GROUND WPT

Initial ground to ground WPT applications will mainly be for demonstration and development purposes, as there are much more cost effective means for short range power delivery on the surface of the Earth, such as high voltage transmission lines or undersea cables. Long range point-to-point WPT via exoatmospheric reflectors [2] will be discussed later.

The demonstrations of WPT must nevertheless provide for warning or excluding personnel from the beam such as with barriers or fences, if the power flux density exceeds the ANSI/IEEE C95.1 levels for controlled or uncontrolled environments as appropriate (of order 5mW/cm², depending on frequency). Signage in various languages must be displayed to warn interlopers of the hazard and to alert those who wear potentially susceptible electronic devices for health reasons. Proximity detectors and loudspeakers may also be required, depending on the hazard level and location. Eyesafe visible laser surround beams may be used to outline the invisible WPT beam areas, providing there is adequate particulate matter in the air to scatter their beams. The laser intensity must be in compliance with applicable FDA regulations.

Depending on the microwave power beam intensity, there may need to be avian detectors or screens to exclude fly through. The hazard can be determined by calculating the avian radar absorption cross section and the RF wavelength can be used to determine the specific absorption rate or SAR. This result should be compared to the power expended for flight, to determine if its significantly small. The ratio of eyeball diameter and dielectric constant should be compared to RF wavelength to investigate any resonant-structure, enhanced-heating effects for particular species.

If screens are needed, but are impractical due to the geometry, then for high beam intensity cases the avian detectors must be interlocked with the power beam transmitter such as to douse the beam during transit of the species to be protected.

This beam turn-off strategy would then involve having alternate switched or floating energy storage at the receiving site to prevent interruption of power delivery from the rectenna. Also, the necessary electrical transient suppression must be provided to protect the WPT equipment during the turn-off, turn-on transients. As no rotating mechanical mass is involved in the power conversions, the beam quenching can be near instantaneous. This is desirable from the point of safety. However, the sudden interruption of DC current flow can produce large electrical transient voltages unless the systems are designed for proper overvoltage suppression with the appropriate added equipment.

Noise makers or other devices may be used to try to detour the avian hazards to prevent some interruptions. The avian detectors may be radars, IR or video units with binocular equipped personnel and instrumentation for beam control as backup or in special circumstances (areas with American eagles, whooping cranes, etc.).

Similar considerations may apply for areas with low flying aircraft, ultralights, hang gliders, etc. Notices to airmen or NOTAMS may be required to alert those that may potentially be affected by beam crossing, ground reflections or overspray or diffraction about the rectenna.

The FCC or NTIA, FAA, EPA, FDA, etc. will need to be informed and permits obtained for experimental or other purposes. Local ordinances, licenses, environmental studies, environmental mitigation's etc. will need to be handled per existing policies at the local, regional, state and federal levels,

Adequate policy probably exists to cover safety concerns and in support of permitted commerce for most short range ground to ground WPT applications.

Space policy considerations may only come into play if there are high levels of overspray of the beam around the rectenna, that result in significant beam intensities in low earth orbit (LEO).

The damage to spacecraft operations or equipment from intercepting a WPT beam may be the following: 1.) temporary disruptions of electronics functions caused by the transient coming through the spacecraft radio links-so called " front door" entry. 2.) transient electronic upset events that may come through electromagnetic field leakage through cracks in cases or unshielded cables, etc.- so called "back door" entry. These events can either cause 3.) electromagnetic interference (degradation of Signal to Noise ratio, SNR) or 4.) electronics disruptions (dropped or added bits or bias), that the spacecraft may later recover from and potentially survive.

Should space policy considerations involve requiring large enough beam stops or beam dumps to intercept the spillover down to certain levels, restricting transmit times to avoid

satellite interceptions, restricting angular regions of beam transmission, restricting satellite orbits to avoid beam interruption, etc.?

Higher level beam overspray ($> 200\text{V/m}$) could lead to 5.) permanent semiconductor device operating parameter changes without recovery, or in even more intense cases, 6.) fusing open junction connections or wires or 7.) other serious dielectric or structural heating leading to distortions or total failures of other spacecraft subsystems than the electronics.

In those latter cases, however, beams of such intensity may only involve weapons grade applications and thus "policy by other means" may be applicable.

GROUND TO AIR-PLATFORM APPLICATIONS

After precursor ground to ground WPT applications, the next commercial or scientific applications of WPT may involve transmitting power to high altitude, nearly geostationary platforms at around 70,000 ft altitude [3]. Such platforms will first be used for telecom relay [4] and observation functions. At that altitude, there is a minimum of energy required to station keep a circling aircraft, a helicopter or an airship. Also, the horizon is approximately 500-mi. radius. Solar power may suffice for some lightweight payloads in the future if adequate energy storage is developed, but most commercial applications will require larger electric power in support of useful commercial payloads of long duration.

In this application, the beam crossing of controlled airspace will certainly involve policies concerning the FAA. The overspray around the rectenna may then also involve spacecraft from various countries and thus space policies.

In the future, such platforms may permit alternate casino and entertainment, or vacation venues [5]. Thus the power beams will grow in intensity as the size and power requirements for the platforms increase to support stratospheric tourism. Shuttle aircraft will have to safely navigate around the beam.

The WPT system economics will prefer that the beam overspray be kept small, which will assure that mostly communications interference potential will be the major spacecraft concerns. However, avian beam crossers will be of concern in addition to aircraft or airship crossings between the ground based transmitter and the rectenna. A means of outlining or marking the beam is desirable and will be discussed later.

What space policy considerations are needed for handling WPT beam overspray to near geosynchronous airborne platform operations? Are the overspray regions spatially well enough defined to require that satellite orbits be designed to not intercept such regions, or shall all beamers quench their beams during flyover?

HIGH-ALTITUDE POWER RELAY PLATFORMS

With the maturing of telecom and observation platforms will come applications for using similar high altitude platforms for power beam relay between Earth and spacecraft. For example, microwaves could be used between the Earth and the platform, with subsequent conversion of energy to a laser beam or beams to supply power to spacecraft during eclipse periods. This would allow an all-weather WPT system with small footprint beam on the spacecraft photovoltaics.

In this case, space policy must consider the short wavelength power beam crossing between the stratosphere and the spacecraft. Beam interruptions are commercially undesirable, but unintentional spacecraft zapping is also undesirable. Sensors could be blinded temporarily or in the case of very high power flux densities, permanently. Who shall have the right-of-way in such cases, the power beam or the intruding spacecraft?

EARTH TO SPACE POWER BEAMS

Bill Brown and Peter Glaser proposed a "Transportronics" system of multiple beams around the Earth's equator to power electric thrust orbital transfer vehicles between LEO and GEO [6]. Located at ground sites around the equator, such beaming sites could pose a potential hazard to aircraft or other spacecraft. Interrupting such transportation power beams for safety reasons will affect navigating the transport spacecraft.

High power laser beams for propulsion schemes to place payloads in orbit such as Leik Myrabo [7] proposes using pulsed thrusting air or propellant breakdown, definitely use hazardous power beams. However, their duration and spatial volume encountered are predictable and thus can be engineered to be safe under most circumstances. Nevertheless, issues of space policy arise due to the potential conflicts of commerce (launches) and beam safety to other spacecraft already in orbit. Blinding spacecraft sensors or thermally heating structure enough to support degradation in function are undesirable.

Existing Spacetrack radars and data bases should be beefed up to accommodate giving predictions to commercial power beamers to aid in avoiding hosing down existing spacecraft. Similarly, the air traffic control system radars and data bases could be used to avoid the microwave beams encountering controlled air traffic.

Uncontrolled air traffic will require additional platform or separate, additional ground based radars operated by the commercial beamers to sense approaching vehicles. The combined spacecraft avoidance and aircraft avoidance will lower the duty cycle for power transfer. This along with the cost of the sensors must be factored into the overall system economics.

Shall WPT beamer launch locations be given priority of beam space use during certain periods of the launch or recovery phases of transportronics?

If such transportronics beams cross over international borders, is the energy in the beam a property of the transmitting country during the overcrossing?

SPACE TO EARTH POWER BEAMS VIA RELAY PLATFORMS

Given the technology to operate high altitude relay platforms for space directed beams, it should be only a short time until Earth directed beams are also possible. Economics is yet to be established, but one could deliver converted sunlight power in orbit via laser beam to a high altitude platform for subsequent conversion to microwave beam to beam to a rectenna on Earth that may be in eclipse. Again, an all-weather power delivery scheme.

The laser wavelength could be selected to have maximum absorption in the Earth's atmosphere, as the platform is above most of the atmosphere. This would promote beam safety by making it difficult to zap the surface of the Earth with the laser beam. Currently however, the existing photovoltaic material's band gaps do not yield efficient power conversion at such wavelengths (Private communications with Geoff Landis). The microwave relay beam to the ground will be larger in diameter and thus less intense.

Space policy would be concerned with lower altitude spacecraft that may intercept or be intercepted by the laser beam. Shall policy restrict this application to certain orbits or to certain restricted locations?

SPACE TO SPACE WPT

Space to space power beaming such as from the space station to a coorbiting free flyer for g-isolation experiments or commercial weightless materials processing involving high power levels, may present hazards to extravehicular operations. As there is little orbital debris to scatter the beam, even visible wavelength laser beams will not be noticeable. This is a definite safety hazard. However, technology may provide a solution.

It may be desirable from the safety point of view to require that such invisible power beams be required to have a minimum of intensity along their axis, or a hollow center into which very diaphanous particles are injected near the transmitter to scatter visible wavelengths or to render visible, the microwave and IR beams. Luminescent particles activated by the power beam photons may be required in shadow or eclipse situations, whereas sunlight scattering particles will suffice for daylight operations. The beam shape can be similar to the monopulse beam used for radar tracking purposes [8].

The particle densities should be such as to not be an orbital debris hazard. Mass can be conserved by periodically deploying the highlighting particles instead of having a continuous stream. Suitable particle generators and means for their efficient delivery to the center of the beam must be developed.

The lightweight particles would be propelled by radiation pressure along the beam and constrained by flow physics within the power density gradient until such time as they eventually diffuse out of the beam. Thus outlining the centerline of the power beam. This scheme would require optics or antennas that are about three times the diameter of simple Gaussian beam optics for efficient beam coupling, but the increased beam safety may be a policy requirement for extra vehicular operations in the vicinity of beamed power.

Policy may aid in developing a universal standard color and/or beam highlighting interruption length to code the various wavelength beams. That is, short pulse lengths of particles may identify short wavelength, tight beams and longer particle streams may identify the longer wavelength, larger diameter microwave beams. Color differentiation could be used to denote the beam intensity so as to give warning for safe standoff or avoidance distances.

Given the beam visibility marking, then should the policy be to require additional beam interception detectors, or should the policy be to let the intruder beware, much as high power transmission line practice?

DIRECT SPACE TO EARTH POWER BEAMING

Direct to Earth power beaming such as the Peter Glaser SPS concept using microwave beams, requires different space policy considerations at the two different ends of the power link.

At the receiving end of the link, the normal power flux densities in the peak of the beam ($\sim 23 \text{ mW/cm}^2$) are low enough at the rectenna that visible beam marking may not be required there. The power density at the edge of the rectenna is approximately 1/10th that at the center, and decays further at the exclusion fence boundary around the site. Only when

there is a transient event such as loss of load or shorted load at the rectenna will the combination of incident and reflect power significantly increase the power density in the space above the rectenna aperture.

In the worst case scenario, the doubling of electric field strength could result in four times the power density or 93 mW/cm² in certain standing wave positions, but hopefully only for the duration of the transient to be detected and acted upon. Due to the continuous transmitted beam of energy, the power-in-the-pipe will continue to exist for a minimum of the round trip light time to the SPS (~ 1/4 second) that is required for a shut-off signal to reach the spacecraft and then for the beamer to reduce its output power, as seen at the ground.

However, because of phase focusing effects in the aperture, the beam intensity maximum at approximately $0.2 D^2/\lambda$, (~ 1,635 km) in front of the transmitting array is strong enough (33kW/m² for 6.25 GW, 1 km dia. @ 2.45 GHz) to be of concern for spacecraft that may traverse it at that altitude [9]. (D= transmit aperture diameter and λ = RF wavelength.) For a tapered aperture distribution, the on-axis peak power density may be over 26 times (14 dB) the far field power density at $2.0 D^2/\lambda$. [10, 11].

If the beam intensity must be reduced to accommodate a spacecraft incursion into the beam, the beam must be either diverted, dimmed or doused. The beam can be diverted by placing a linear phase taper across the transmitting phased array aperture or the array can be mechanically steered off its normal pointing direction. The latter action is very slow, whereas the former can be electronically swift, limited only by the speed of light time across the aperture.

Diverting the beam may not suffice, depending on the range of the spacecraft and its trajectory relative to the SPS. In that case, it may be necessary to de-phase the transmitting array by allowing random noise to set the phase of each array element. This action broadens the beam and drops the intensity by about a factor of $1/N$, where N is the number of elements in the transmitting array, which may be thousands.

If the above actions do not sufficiently reduce the beam intensity, then more drastic action is required, with more severe consequences to the system than just a reduction of the rectenna output.

The sudden reduction in rectenna output sets up electronic transients in the customer power connection, unless protective measures are applied, such as snubbers to damp overvoltage spikes, or if the ground system can switch to an energy storage system rapidly, or if a battery like charge storage system is floating on the rectenna output DC lines. Flywheels may suffice for short time outages to allow a spacecraft to traverse the beam width, for example.

All of these equipment add perhaps 10-25% more to the capital and operating/maintenance costs to the SPS power system in order to provide uninterrupted power delivery when other spacecraft must pass through the beam.

If the intruding spacecraft is very close to the transmitting antenna, then there is no alternative other than turning off the transmitters, as diverting and dimming will not reduce the beam intensity sufficiently. Turning off the transmitters leads to severe impacts to the transmitter and its solar power converters. Again there are electrical transients, but in addition there are thermal transients of consequence. The SPS system must be able to accommodate the periodic eclipses around the equinox, but they are well known in advance

and planned for. Emergency shut down and restart capabilities will also add to the system cost.

Therefore, space policy discussion and a decision is needed on the best strategy to protect the spacecraft or to avoid illuminating it. Who has the right-of-way in this case, the SPS beam or the beam crossing spacecraft? What level of beam interruptions should the power system designers aim for in order to maintain a quality of service for power delivery?

LONG RANGE POINT TO POINT BEAMING FROM EARTH VIA ORBITING REFLECTORS.

The intercontinental beaming of wireless power via orbiting reflectors will principally be via geosynchronous (GEO) orbit mirrors [12]. The power beams in a circuit must penetrate the air and space paths twice, thus increasing the potential for collisions with aircraft and spacecraft and lowering the effective duty cycle. Again, as a matter of space policy who is to have the right-of-way, the beams or the crafts, and under what conditions?

Shall the beams be restricted as to time and period of operation? Shall the spacecraft orbits be restricted so as to minimize beam interceptions? Shall the beam directions be proscribed or otherwise constrained to minimize space traffic disruption? Who will have right-of-way and when and how will they know it?

SPACE POLICY CONSIDERATIONS

Should beam-free zones be instituted such as to permit unrestricted space flight zones? Should certain orbit positions be prescribed and other proscribed? Should power beaming be restricted to odd numbered seconds of GMT minutes, even minutes of hours or odd hours of the days? Should beam allowed corridors or even quadrants of space be designated where spacefarers should be alert to potential beam movements that they move in at their own risk? Should beams in certain regions be restricted to a particular frequency or wavelength so that spacecraft can be designed to be well shielded at those specific frequencies and thus coexist?

Should zapping protection for beamed power to or from space be extended to only certain birds? What about protection for bats, flying squirrels, moths, or for certain insects?

What should be the space policy for fines or restitution or estate compensation in cases of errant beam trespass or errant spacer intrusion resulting in commercial or other economic loss or loss of life?

Who or what agency should be responsible for beam safety system design oversight, performance verification, monitoring compliance in free flight zones or in flight restricted zones in space?

Who should investigate whether there should be a policy to require a standard low-level, visible "pilot" beam to occupy the space of a high power beam when it is not turned on. Much as the tracks for a train, when the train is not present. Thus people will know that a high-speed "train" of electromagnetic energy may come roaring down such "tracks" at any time.

Should there be a space policy to establish an independent organization whose function is to know if the beam intercept detectors are functioning properly? Would you trust your sister to fly through a beam whose safety system gives you no assurance that it is properly

functioning? What should be the space policy relative to beam safety system operability disclosure? Who knows and when did they know? How do they know? Can they individually initiate a beam interception test with an unpersoned surrogate vehicle for example? How frequent should such events be? What should be the cost for such a beam interruption and who should bear the charges? How is it to be enforced and the compensation collected?

These are space policy issues that have safety and commercial economic implications for SPS and wireless power transmission.

After transportation to space, the second most important item is power in space. Some high level of priority should be given to considering power beaming policy issues for support of exploration and economic activities in space. Such policies will greatly influence the economic feasibility of Space Solar Power (SSP).

Space policies in support of beamed power are desirable for their energy transport benefits to humanity.

More Power To Us.

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